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# IDENTIFYING HEAVY-ION-BEAM FUSION DESIGN AND SYSTEM FEATURES WITH HIGH ECONOMIC LEVERAGE*

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## ABSTRACT

We have conducted parametric economic studies for heavy-ion-beam fusion electric power plants. We examined the effects on the cost of electricity of several design parameters: maximum achievable chamber pulse rate, driver cost, target gain, electric conversion efficiency, and net electric power. We found with reasonable assumptions on driver cost, target gain, and electric conversion efficiency, a 2-3 GWe heavy-ion-beam fusion power plant, with a chamber pulse rate of 5-10 Hz, can be competitive with nuclear and coal power plants.

## INTRODUCTION

One of the primary objectives of the Inertial Confinement Fusion (ICF) Applications Group is to develop power plant concepts that will be economically competitive with other long-term electric power producers (e.g., with fission and coal). We are developing systems models for ICF power plants that allow us (1) to identify design features that have the highest leverage for improving ICF economics and (2) to do first order economic comparisons with other power sources. In this paper we expand on the results given in Ref. 1.

Our economic model is based on a heavy-ion-beam (HIB) fusion power plant that consists of a driver, a target factory, and one or more power units. A power unit is defined as all the buildings and equipment needed to generate electric power, provided the target and beams are delivered to the reaction chamber. Because the maximum achievable pulse rate in a single chamber is limited, more than one reaction chamber may be required to achieve the desired output of a single power unit. We distinguish between multiple power units and multiple reaction chambers so that we can examine separately the effects of increasing the number of reaction chambers at a constant net power and of increasing the power level by driving more than one full-scale power unit with a single driver. In Fig. 1, a power plant with two power units is illustrated. Each unit has two reaction chambers, each of the chambers equipped with beam lines and a target injector.

While economic factors are not the only ones that are considered when making decisions about future power sources, such factors as safety, environmental impact, reliability, technical risk, and public acceptance may not weigh heavily unless ICF appears to be economically competitive. How one defines the concept of economic competitiveness is subject to much debate; however, a common figure of merit in similar economic analyses is the cost of electricity (COE), which is defined as total annual costs ($) divided by net electrical output per year ($kW_eh$). Because of economies of scale, the COE will decrease with increasing power plant size. The total capital cost, however, will increase with increasing plant size. Therefore, other figures

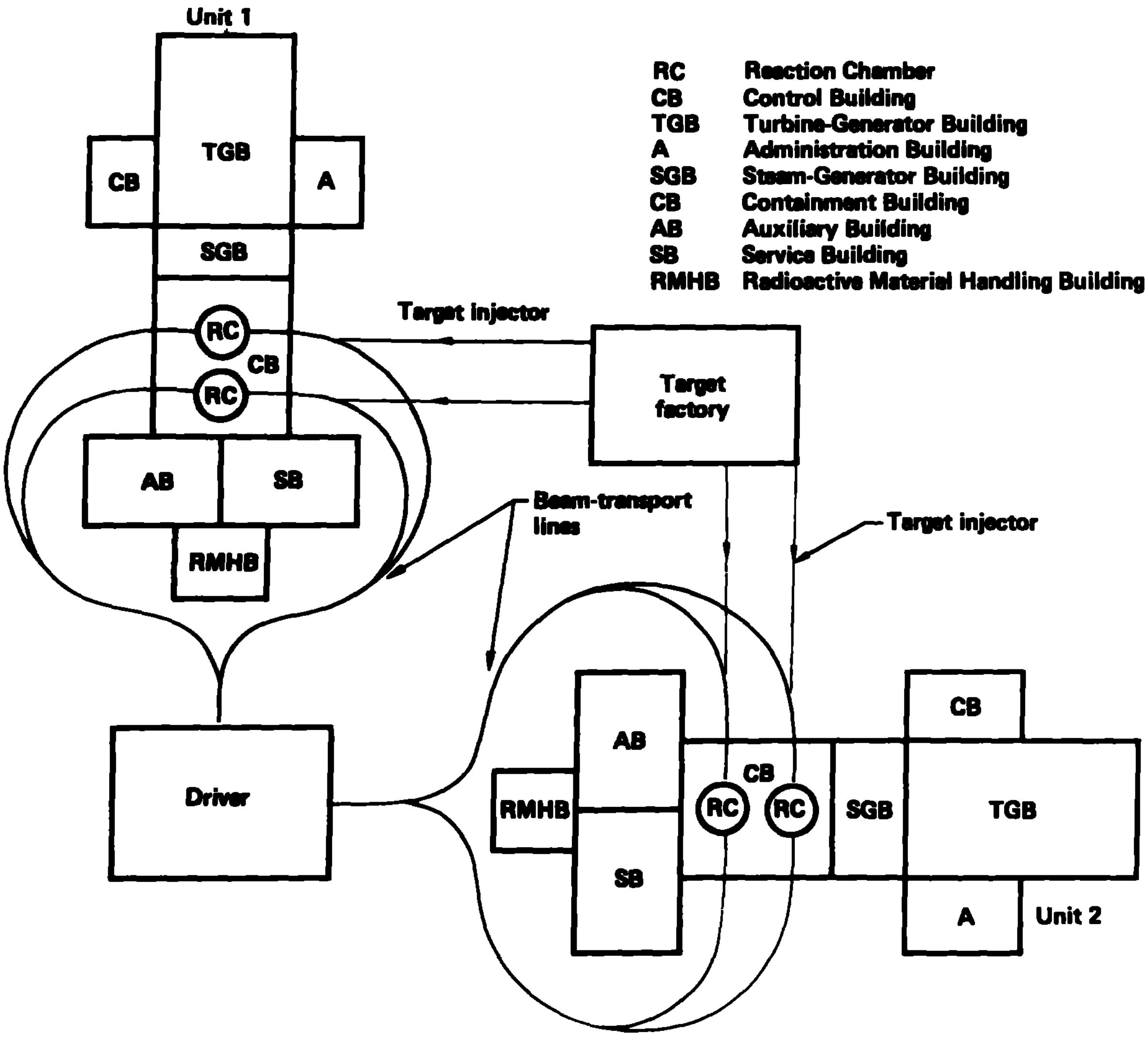


Fig. 1. The elements of a heavy ion beam (HIB) fusion power plant. Several power units may be served by one HIB accelerator and one fusion target factory. Each power unit has everything else needed to produce electricity, including one or more fusion reaction chambers with associated steam supply systems and a turbine.

of merit, which reflect the dollars at risk before income begins, are also useful. One example is a weighted sum of the COE and total capital investment. Our long-term intention is to examine a variety of such figures of merit. However, in this initial report we simply use the COE expressed in constant 1983 dollars so that we can begin to make some relative comparisons.

The COE can be expressed as

$$COE = \frac{RC_{TOT} + M + F}{8760\ N_u P_n \alpha}\ (\$/kW_e h) \quad , \tag{1}$$

where

$R$ = annual fixed charge rate on the capital investment ($yr^{-1}$),

$C_{TOT}$ = total capital cost of the plant ($),

$M$ = annual operation and maintenance cost ($),

$F$ = annual fuel-cycle cost ($),

$N_u$ = number of power units per plant,

$P_n$ = net electric power per unit ($kW_e$),

$\alpha$ = availability factor = 70%, and

8760 = number of hours per year.

We conducted studies to investigate the effects on COE of variations in several design parameters. In particular, we examined the effects of maximum achievable chamber pulse rate, driver cost, target gain, thermal to electric conversion efficiency, and net electric power. The driver pulse rate ($\omega_d$) is the independent variable. In general, for any specified set of parameters, the COE will have a minimum when expressed as a function of the driver pulse rate. This minimum will tell us the optimum operating point. To find this optimum, we must express the costs in Eq. (1) in terms of the driver pulse rate and other factor that are either held constant or varied parametrically.

Based on its forecasts of demand for power, an electric utility must decide what size and type of plant to build if it is to meet that demand. Net electric power is the key measure of the plant's size; therefore, in our analyses, net power is held constant. Any specified total net electric power ($N_u P_n$) can be achieved by operating at low pulse rate with high yield targets or at high pulse rate with low yield targets.

In the next section, we develop the costs as a function of the driver energy ($E_d$), the gross electric power per unit ($P_g$), the number of power units per plant ($N_u$), and the number of reaction chambers per power unit ($N_c$). The power balance for the entire plant will then be examined to relate these factors, and thus the costs, to the driver pulse rate.

## COSTS

In Eq. (1) the annual cost is expressed as the sum of the portion of the capital costs attributable to each year of operation ($RC_{TOT}$), the operating and maintenance costs (M), and the fuel-cycle costs (F). Each of these will be examined in turn, with all costs expressed in constant 1983 dollars. Absolute values of the COE found in this study should be treated with the same skepticism given to any attempt to project costs so far into the future. Our intent is to use the results in a relative sense for two reasons. First, the relative impact on the COE of various design changes can be accepted with much more confidence than the absolute numbers. Second, the economic factors we use are based on assumptions similar to those used to estimate the COE for future fission and coal power plants.[2] Therefore, relative comparisons of the COE ought to be reasonable.

It should be noted that for fusion power plants, fuel-cycle costs will be small compared to $RC_{TOT}$, and M will be taken as proportional to $C_{TOT}$. Thus COE is also proportional to $C_{TOT}$ and, therefore, the relative impact of design changes will be independent of economic assumptions contained in R and other multiplicative factors.

## Fixed Charge Rate

The fixed charge rate, R, is the average annual equivalent cost per dollar of capital investment over the life of that investment. It includes return on the investment, return of the investment, income taxes arising from the investment, and property taxes, and interim replacement costs. The derivation of the fixed charge rate is given in Appendix A. For our constant dollar analysis, the fixed charge rate is 10.5%.

## Total Capital Cost

The total capital cost for the power plant is the sum of the total capital costs of the power unit(s), driver, and target factory. The total capital costs include direct capital costs, indirect capital costs, and time-related costs.

$$C_{TOT} = (C_u + C_d + C_t)\, f_{CON}\, f_{TC} \quad , \tag{2}$$

where $C_u$, $C_d$ and $C_t$ are the sums of the direct and indirect capital costs for the power unit(s), driver, and target factory, respectively, $f_{CON}$ is contingency factor, and $f_{TC}$ is a time-related cost factor. We assume for this study that we are considering a completely mature technology. Therefore, consistent with Ref. 2, a contingency of 10% ($f_{CON}$ = 1.1) is chosen. The time-related cost factor for a constant dollar analysis is derived in Appendix B and found to be $f_{TC} \simeq 1.1$.

## Power Unit Cost

The model we have assumed for the HIB fusion power plant (Fig. 1) uses a conventional steam cycle to produce electricity. The fusion power unit looks essentially like a fission power plant, except that the fusion chamber replaces the fission reactor vessel. Because of these structural similarities, we derive our cost-scaling models from recent estimates for future fission plants.

Fission power plants recently completed and currently under construction are significantly more expensive to build than coal-fired power plants. However, researchers in the Engineering Technology Division at Oak Ridge National Laboratory and the United Engineers and Constructors have estimated the cost of nuclear power plants for the 1990s based on the presumed effects of licensing reform.[2,3] The reforms in House bill H.R. 2511, Nuclear Licensing and Regulatory Reform Act of 1983, include provisions for preapproved plant designs, early site approval, and single-step licensing, as well as reduced regulatory changes that result in major changes to the plant design. The retrofitting required by continuous changes in regulations has had a major impact on the construction and engineering costs of nuclear power plants built in recent years. The 1990's nuclear plants have direct capital costs essentially equal to those of coal plants. We assume that the fusion power unit can achieve similar direct capital costs for those elements not unique to fusion.

The capital cost quoted in Ref. 2 is for a single-unit, pressurized water reactor (PWR) with a net electric output of 1.10 $GW_e$. (The gross electric power is about 1.16 $GW_e$.) This report also states that the costs can be scaled to alternate size plants by raising the electric power to a scale factor, a, of less than 1. That is

$$C_1 = C_0(P_1/P_0)^a \quad , \tag{3}$$

where $C_0$ and $C_1$ are the costs for plants with electric powers of $P_0$ and $P_1$, respectively. Reference 2 gives a scale factor for each major direct and indirect capital cost account. The cost-weighted average for direct costs is 0.6, while the cost-weighted average for indirect costs is 0.4.

The direct capital cost estimate for this PWR is $0.77 billion (January, 1983 dollars)[2]. The indirect costs, which include construction, home office engineering, field office engineering, and owners' costs, total 50% of the direct capital costs.[2] While this is a much lower fraction than currently experienced in nuclear power plant construction, it is consistent with the indirect costs for the period preceding the Three Mile Island accident. Thus, the cost of a single-unit nuclear power plant is given by

$$C_{un} = 0.705P_g^{0.6} + 0.363P_g^{0.4} \ \$B \quad , \tag{4}$$

where $P_g$ is the gross electric power in $GW_e$. The first term is the unit direct capital cost, $C_{ud}$, and the second term is the unit indirect capital cost, $C_{ui}$.

Now let us find an expression for the cost of a single fusion power unit. As previously indicated, each fusion power unit may have more than one reaction chamber associated with a single set of turbines. To account for this in our cost algorithms, we break down the direct capital cost into three parts: the containment building cost, the steam-supply-system (SSS) cost, and the cost of the remainder of the power-unit.

As previously noted, the fusion power unit we are studying looks essentially like a fission plant. The cost of the remainder of the power unit includes the turbine plant equipment, electric plant equipment, miscellaneous equipment, heat rejection systems, reactor plant equipment not in the SSS, and all structures except the containment building. (The driver and target factory are treated below.) Thus, we assume the cost and scaling for this remainder are exactly the same as for a fission plant. The SSS of a fission plant contains the reactor vessel, the primary coolant loop (and secondary, if used), as well as the heat exchangers and steam generators. The costs of these are a function of the plant's thermal power (but can be expressed as functions of the electric power for a given conversion efficiency). In a fusion plant, all parts of the SSS, except the reaction chamber, will cost and scale like the corresponding elements of a fission plant. The cost of the reaction chamber itself may be a function of the fusion power or the pellet yield, depending on what phenomena are limiting the chamber's size. In any event, the cost of the reaction chamber is a small part of the cost of the SSS which, in turn, is a small part of the cost of the whole power unit. Therefore, we will ignore the yield dependence and will scale the entire SSS cost for a fusion plant in the same way nuclear SSS costs are scaled for fission plants. Similarly, though the containment building cost for a fusion power unit may be much less than for a fission reactor, the containment building cost is a small fraction of the total cost. For this reason, we choose to equate them.

Reference 3 gives a detailed breakdown of the cost of the PWR for the 1990s. It shows that the PWR containment building cost is 7.5% of the total direct cost, and that the SSS accounts for 18.2% of the total direct cost. We allocate additional containment building space and SSS equipment for each additional fusion chamber. Using these same fractions for fusion, the direct capital cost of the power unit can be rewritten as

$$C_{ud} = 0.705[0.743P_g^{0.6} + 0.075P_c^{0.5}N_c + 0.182P_c^{0.6}N_c]\ \$B \quad , \tag{5}$$

where

$P_g$ = the gross electric power for a single power unit, in $GW_e$

$P_c$ = the gross electric power associated with each chamber ($GW_e$), and

$N_c$ = the number of chambers per power unit.

Hence, $P_cN_c$ is equal to $P_g$ for each power unit. Note that the cost of the containment building and SSS equipment are first scaled to the appropriate size and then replicated. The 0.5 scaling factor for the containment building cost and the 0.6 scaling factor for the SSS cost are the values suggested in Ref. 2 for structures and reactor plant equipment, respectively. For example, the direct capital cost of a 1.0-$GW_e$(gross) power unit with a single chamber is \$0.705 billion, whereas a 1.0-$GW_e$ power unit with four chambers is \$0.853 billion, or 21% higher. We assume that the indirect costs ($C_{ui}$) are the same as for a fission reactor:

$$C_{ui} = 0.363\ P_g^{0.4}\ \$B \quad . \tag{6}$$

Since the power-unit cost increases less than linearly with increasing power, it is clear that economy of scale will make it most cost effective to build the largest power unit possible. For a variety of reasons, however, this is not always the most desirable decision to make. It may be better to build several smaller power units at the same location (e.g., reliability may be better and the modularity allows one unit to start contributing income while the second is being built). In an ICF power plant, a single driver and target factory can be used to serve more than one power unit. The cost of these components can, thus, be divided between the units, thereby lowering their impact on the COE. Experience has shown that there are savings in both the direct and indirect capital costs for multi-unit power plants.[2,3,4] Typically, each additional unit has a direct capital cost equal to 80% of the direct capital cost of the first unit on the site, and an indirect capital cost equal to 60% of the indirect cost for the first unit. Using these factors for the multi-unit fusion power plant enables us to express the total cost of all the power units ($C_u$) as

$$C_u = (0.2 + 0.8\,N_u)C_{ud} + (0.4 + 0.6N_u)C_{ui} \quad , \tag{7}$$

where $N_u$ is the number of power units sharing a single driver, and $C_{ud}$ and $C_{ui}$ are the direct and indirect costs of a single power unit given in Eqs. (5) and (6).

## Driver Cost

The costs of a HIB driver are not well known at this time. They have been estimated in the HIBALL study[5] for a radio frequency accelerator and by Herrmannsfeldt[6] based upon studies conducted at the Lawrence Berkeley Laboratory (LBL) for an induction linac. New estimates are being generated by

LBL in a current Department of Energy study; however, until those estimates are available, we will use the previous results. The driver direct capital cost ($C_{dd}$) is given by[5,6]

$$C_{dd} = 0.64E_d^{0.4} + 0.1(N_c N_u - 1)\ \$B \quad , \tag{8}$$

where $E_d$ is the driver beam energy in MJ. The second term in Eq. (8) accounts for the additional cost of transporting beams to the individual reaction chambers. Note that the cost relationship above does not depend upon driver pulse rate. While this is not strictly correct, it is often maintained that in the range of interest, the dependence on pulse rate is very weak. The indirect capital costs for the driver are also taken as 50% of the direct capital cost. Therefore,

$$C_d = 1.5\ C_{dd} \quad . \tag{9}$$

Target Factory Cost

No detailed conceptual design studies have been conducted to determine what an inertial fusion target factory would look like and cost. In other production facilities, such as those in the semiconductor industry, the cost of the factory is a function of the size of the building required to house the production equipment. It has been estimated that the direct capital cost of a target factory with seven process lines would be less than $100 million (Ref. 7). Since it is not clear how the cost varies with production rate and since the total target factory cost does not appear to be large compared to other costs, we will use a constant. Indirects costs totaling 50% of the direct cost are added to the target factory cost. Therefore,

$$C_t = 0.15 \ \$B \quad . \tag{10}$$

Fuel-Cycle Cost

The materials used in the production of the fusion targets are recyclable, for the most part. The primary consummables in the fusion fuel cycle are deuterium and lithium. We have allocated 1¢/target for material costs. Therefore, the annual fuel-cycle cost is

$$F = 3.15 \times 10^5 \ \alpha\omega_d \ \$ \quad , \tag{11}$$

where $\alpha$ is the availability factor, and $\omega_d$ is the driver pulse rate in Hz.

Operation and Maintenance Cost

Annual operation and maintenance costs for the power plant are taken as a fraction, 2%, of the total plant capital cost.[8] Therefore,

$$M = 0.02 \ C_{TOT} \quad . \tag{12}$$

Power Balance

As previously stated, the independent variable in our analyses is the driver pulse rate ($\omega_d$). Since the power unit costs are expressed as functions of the gross electric power ($P_g$) in Eqs. (5) and (6), we must relate $P_g$ to $\omega_d$. This can be done through the power balance for the plant, which is shown in Fig. 2. As indicated in Fig. 2, the gross electric is

$$N_u P_g = M_f \eta_d P_d G \eta_c \quad , \tag{13}$$

where $N_u$ is the number of power units per plant, $M_f$ is the fusion energy multiplication factor, $\eta_d$ is the driver efficiency, G is the target gain, and $\eta_c$ is the thermal-to-electric conversion efficiency.

The fusion energy multiplication factor is the ratio of the total energy deposited in the fusion chamber to the fusion energy. This factor is greater than 1 due to exothermic nuclear reactions within the blanket, [e.g., the $^6Li(n,\alpha)T$ reaction which releases 4.8 MeV]. We use a value of 1.15 which is fairly representative of the ICF chamber concepts we have studied.

The electric power recirculated to the driver is simply

$$P_d = E_d \omega_d / \eta_d \quad . \tag{14}$$

Therefore, the gross electric power per unit is

$$P_g = M_f F_d \omega_d G \eta_c / N_u \tag{15}$$

For any particular case we consider, $M_f$, $\eta_c$, and $N_u$ will be fixed (or varied parametrically). Therefore, we now have $P_g$ as a function of $E_d$, $\omega_d$ and G. The target gain, however is also a function of G.

The target gain versus driver energy relationship used in our analysis is taken from Ref. 9. The following expression is used for the gain curve for

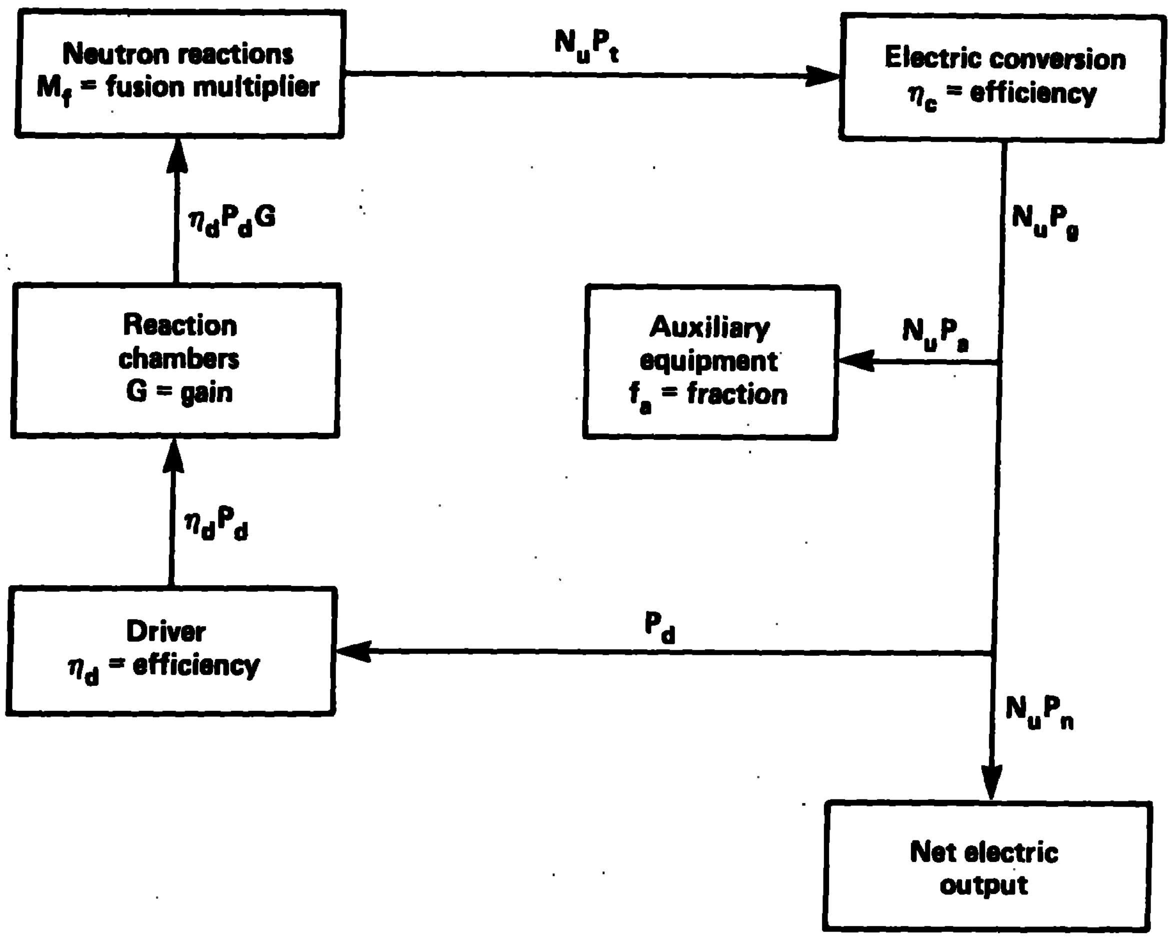


Fig. 2. Power balance diagram for a generic ICF power plant with $N_U$ power units.

single-shelled, cryogenic targets with a $r^{3/2}R$ parameter of 0.01. [r is the focal radius (cm) of the beam and R is the range ($g/cm^2$) of the ions.]

$$G = 20 + 113 \ln(E_d/1.7) \quad , \tag{16}$$

where $E_d$ is in MJ.

For a fixed net power, there is a unique, one-to-one relation between the dirver energy ($E_d$) and the driver pulse rate ($\omega_d$). Therefore, one of these variables can be eliminated from Eq. (15). The net power for the entire plant is given by

$$N_u P_n = N_u P_g - N_u P_a - P_d \quad , \tag{17}$$

where $P_n$, and $P_a$ are the net and auxiliary power per unit.

The driver power ($P_d$) is given in Eq. (14) in terms of the driver energy, pulse rate, and efficiency. The efficiency of the HIB driver ($\eta_d$) varies with the driver pulse rate according to the following relationship:[6]

$$\eta_d = \omega_d/(1 + 4\omega_d) \quad , \tag{18}$$

where $\omega_d$ is the driver pulse rate in Hz. At high pulse rates the driver efficiency approaches 25%. The efficiency decreases with decreasing pulse rate, reflecting that some of the HIB systems operate continuously with a fixed input power requirement.

The auxiliary power per unit is taken as a fraction, $f_a$, of the gross electric power per unit:

$$P_a = f_a P_g \quad . \tag{19}$$

We use $f_a = 0.05$, which is typical of nuclear power plants.[7]

Using the results of Eqs. (14-16) and (18, 19) in Eq. (17), the net power becomes

$$N_u P_n = M_f E_d \omega_d [20 + 115 \ln(E_d/1.7)] \eta_c (1 - f_a) - E_d (1 + 4\omega_d) \quad . \tag{20}$$

For a given choice of $N_u$, $P_n$, $M_f$, $\eta_c$, and $f_a$, we can solve Eq. (20) for $\omega_d$ as a function of $E_d$.

$$\omega_d = (N_u P_n + E_d) \;/\; [M_f E_d G \eta_c (1 - f_a) - 4E_d] \quad . \tag{21}$$

Note that $P_n$ is in $MW_e$ in this expression.

The last thing we must do is choose $N_c$, the number of reaction chambers per power unit. In general, the pulse rate capability of each reaction chamber ($\omega_c$) will not be as large as the pulse rate capability of the driver ($\omega_d$). Therefore, it is assumed that as the driver pulse rate is increased, the chamber pulse rate is increased until a maximum capability is reached ($\omega_{cm}$). At this point, an additional chamber is added. Thus, the number of chambers per power unit ($N_c$) is calculated from

$$N_c = [1 + \text{the integer part of } \omega_d/(N_u \omega_{cm})] \quad . \tag{22}$$

The chamber pulse rate is then

$$\omega_c = \frac{\omega_d}{N_c N_u} \quad . \tag{23}$$

For example, if $\omega_d$ is 30 Hz, $N_u$ is 2, and $\omega_{cm}$ is 10 Hz, then the number of chambers in the plant is 4 (2 chambers per unit, each with a pulse rate of 7.5 Hz).

## RESULTS

The base-case parameters used in our calculations are: $P_n = 1.0\ GW_e$, $N_u = 1$, $\omega_{cm} = 10$ Hz, $\eta_c = 40\%$, $f_a = .05$, and $M_f = 1.15$. Figure 3 shows the net power, driver power, auxiliary power, and gross electric power as a function of the driver pulse rate for the base case. The driver power requirement increases with increasing pulse rate. This follows since a higher pulse rate corresponds to a lower target gain and, therefore, a less favorable overall energy balance for the plant. That is, more power must be recirculated to run the driver and, consequently, a smaller fraction is available to sell. The gross electric power required to maintain a net output of 1.0 $GW_e$ increases from 1.15 to 1.45 $GW_e$ as the driver pulse rate increases from 5 to 50 Hz.

The total capital cost as a function of the driver pulse rate is shown in Fig. 4. The cost has been divided into three components: the power unit, the target factory, and the driver. Because the gross electric power increases with increasing pulse rate, the power unit cost increases, as shown in Fig. 4. The discontinuities, which occur every 10 Hz, are the result of adding additional chambers. (Recall that the chamber pulse rate is limited to 10 Hz in the base case.) The driver cost initially decreases with increasing pulse rate, since higher pulse rates correspond to lower driver energies.

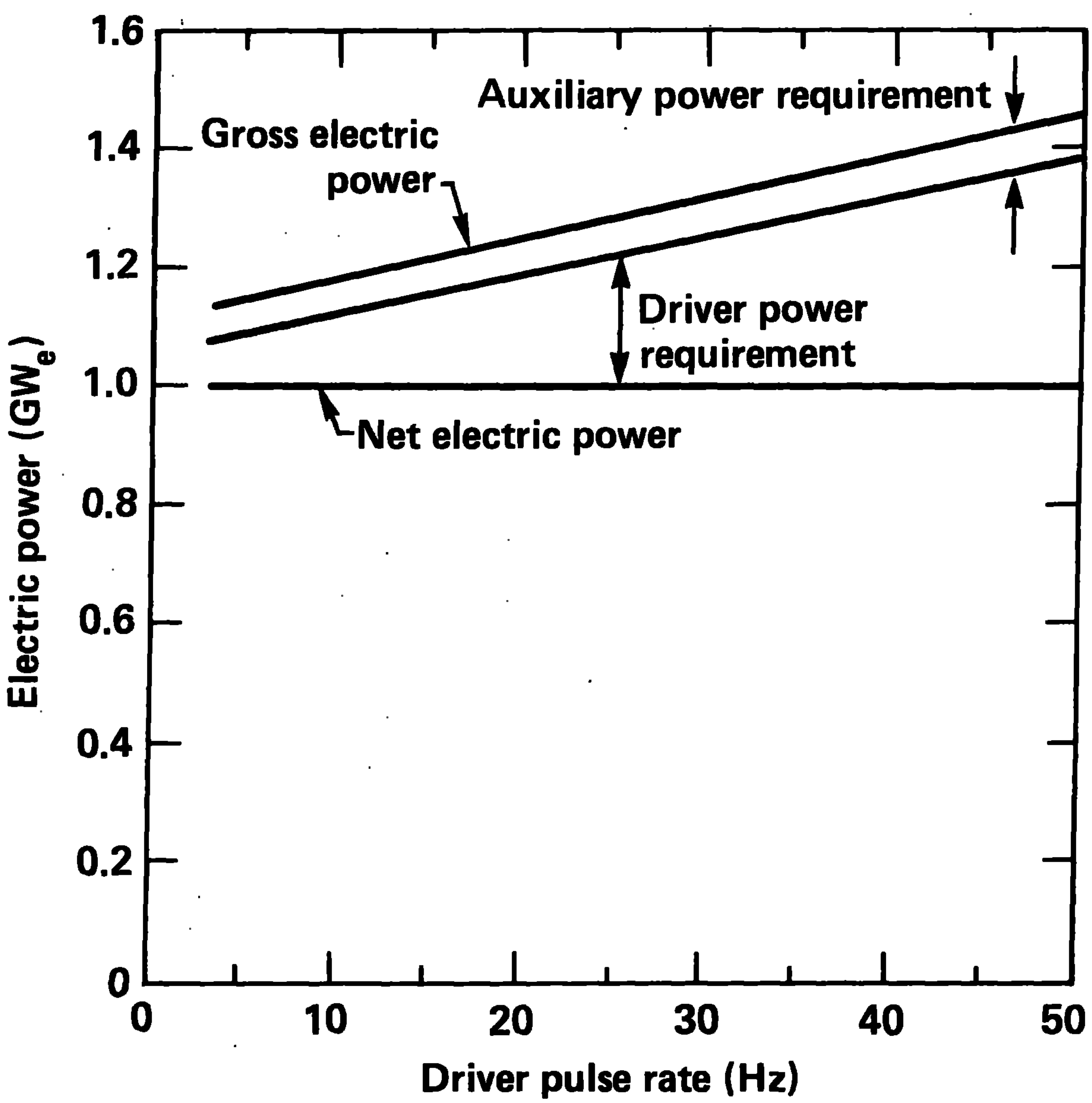


Fig. 3. The gross electric power required to maintain a constant net electric power increases with driver pulse rate.

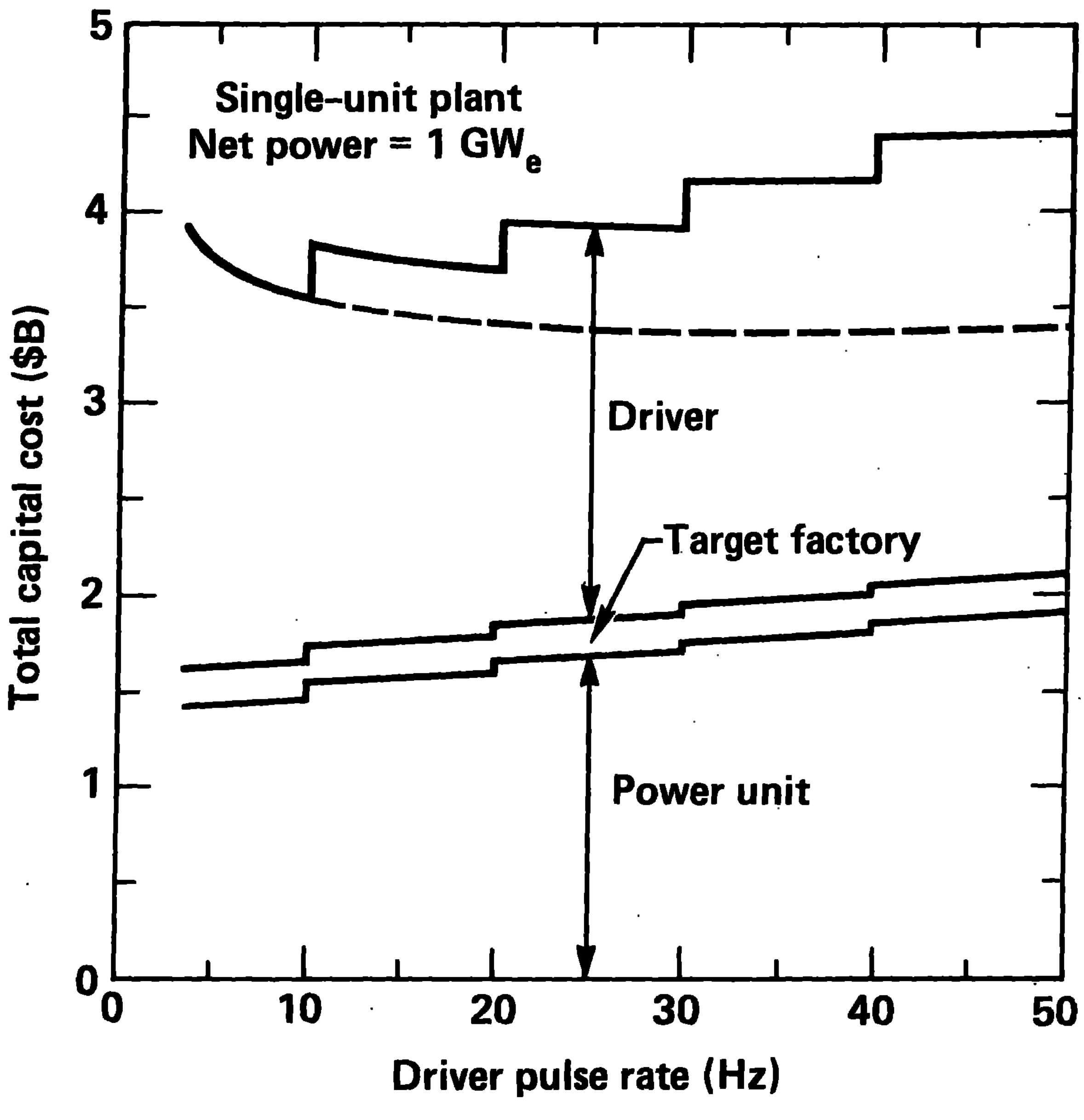


Fig. 4. The HIB driver cost is about half of the total capital cost for a single-unit power plant.

However, there is also a jump in the driver cost every 10 Hz due to the additional beam-transport lines required to supply the added fusion chambers.

The dashed portion of the curves in Fig. 4 represent the continuous function, assuming there is no limit to the pulse-rate capability of each reaction chamber. The minimum total capital cost occurs at 30 Hz, but the curve is extremely flat. This is because the reduction in the cost of the driver is offset by the increasing cost of the power unit. Most of the net cost reduction has occurred by a pulse rate of 10 Hz. For this case, multiplexing chambers to allow taking advantage of a higher pulse rate capability of the driver is not an advantage because the incremental costs needed to provide additional beam lines is so large.

In Figs. 5-12, the COE is used as the figure of merit. While the economic factors used are subject to debate, for the most part, they affect only the absolute value of the COE and not the shape of the curves. Thus, the optima found are not strongly influenced by these economic factors. On the other hand, we can compare these COEs with those of future fission and coal plants if the same methods and economic factors are used. Such an approach leads to COEs of 3.6¢/$kW_e$h for fission plants and 4.6¢/$Kw_e$h for coal plants.

## Maximum Chamber Pulse Rate as a Parameter

The COE as a function of the driver pulse rate is shown in Fig. 5 for four different maximum chamber pulse rates ($\omega_{cm}$): 5, 10, 20, and >50 Hz (unlimited). Focusing on the base case with $\omega_{cm}$ = 10 Hz, one can see that the COE initially decreases with increasing driver pulse rate since the driver cost is decreasing faster than the power unit cost is increasing. The minimum

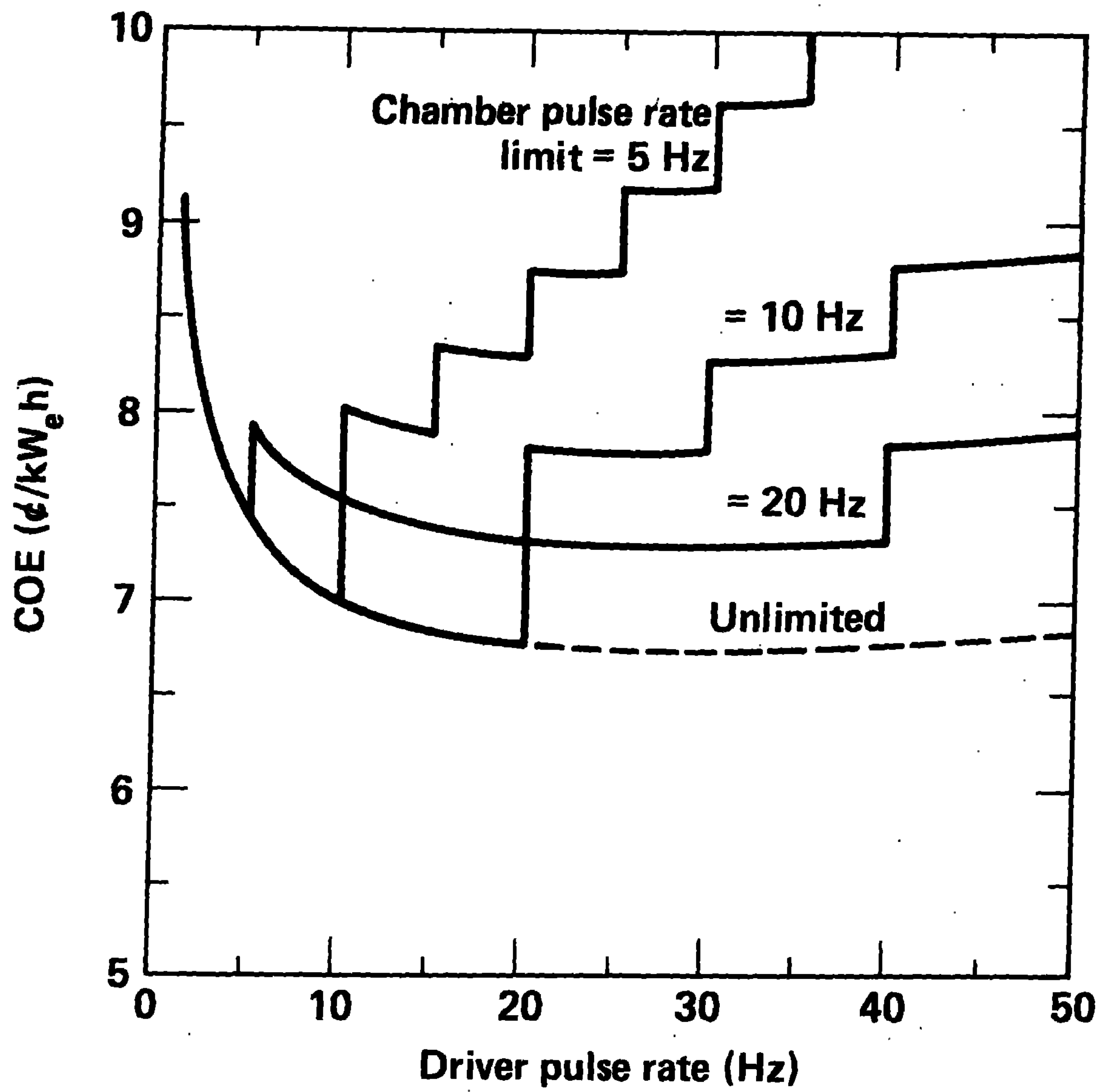


Fig. 5. The minimum COE decreases as the maximum achievable chamber pulse rate increases.

COE is 7.0¢/$kW_e$h for the base case and occurs at 10 Hz. At this point, the driver energy is 3 MJ and the gross electric power is 1.18 $GW_e$. At >10 Hz another chamber with all the associated costs for beam lines and heat exchangers is added. This causes a jump in the COE.

Note the flatness of the dashed line in Fig. 5. If a chamber could be designed to operate at an unlimited pulse rate (or if no cost were associated with increasing the number of chambers), the minimum COE would be 6.75¢/$kW_e$h, which is realized between 25 to 30 Hz. Hence the 10-Hz limit on chamber pulse rate increases the COE by less than 4%. If the chamber pulse rate is limited to 5 Hz, the COE is 7.4¢/$kW_e$h, or less than 10% higher than the 6.75¢/$kW_e$h minimum.

<u>Driver Cost as a Parameter</u>

Figure 6 shows the sensitivity of the COE to the cost of the driver. The three curves, from top to bottom, are the base case, the driver cost reduced by 25%, and the driver cost reduced by 50%, respectively. The cost reductions are applied to the total driver cost, including the additional beam-transport lines required for power units with more than one chamber. In all three cases the minimum COE occurs at 10 Hz. Since the driver cost is a large fraction of the total capital cost (see Fig. 2), reducing the driver cost leads to significant savings in the COE. Each 25% reduction in the driver cost reduces the COE by 13%.

Looking at the dashed curves in Fig. 6 one can see that if the chamber pulse rate is unlimited, the optimum driver pulse rate decreases with decreasing driver cost. In addition, the COE becomes less sensitive to driver pulse rate, and the curves tend to flatten out.

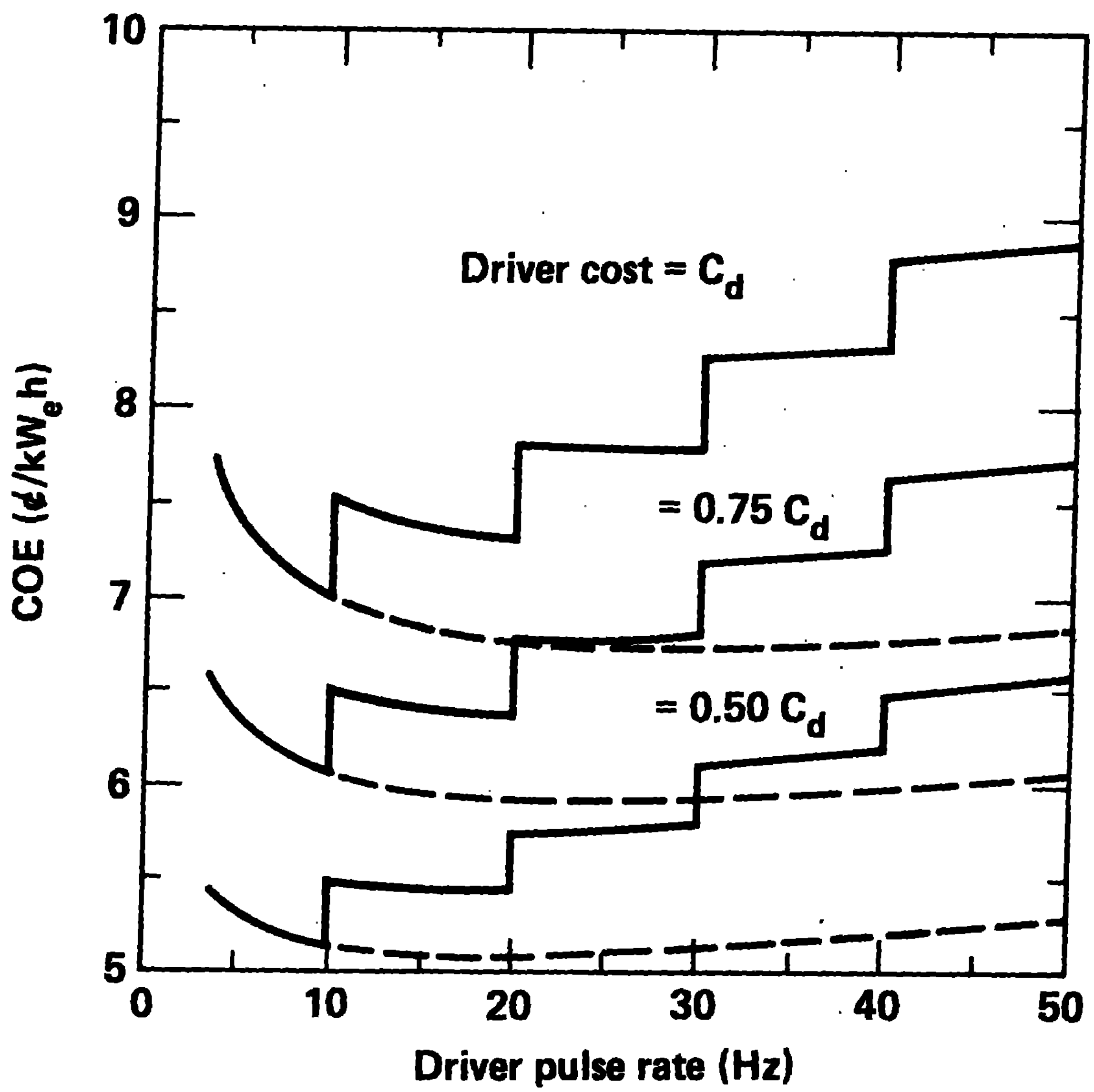


Fig. 6. Reducing the driver cost reduces the COE.

## Target Gain as a Parameter

Improving the target performance also reduces the COE, as shown in Fig. 7. The improved target-gain relationship used to generate these results is based on estimates for polarized fuel. A factor of 3 less driver energy is required to achieve a given target gain using polarized fuel.[10] At 10 Hz the COE is reduced by 12%. The dashed curves show that with no limit on chamber pulse rate, the COE minimum shifts toward higher pulse rate as gain improves at lower driver energy ($E_d$). The COE also becomes more sensitive to pulse rate.

## Electric Conversion Efficiency as a Parameter

Figure 8 shows the COE versus driver pulse rate for electric conversion efficiencies ($\eta_c$) of 40 and 60%. In the models given previously, the power unit costs are a function of the gross electric power and are independent of the electrical conversion efficiency. This is correct for the data base used to derive the scaling relationships. Namely, the 1990's nuclear and coal plants have the same direct capital cost per $kW_e$ even though the electric conversion efficiencies are 35 and 39%, respectively. Therefore, the coal plant has a higher cost per thermal kW. In Fig. 8, we assume that the conversion efficiency can be increased without increasing the cost per $kW_t$. Increasing the conversion efficiency from 40 to 60% only reduces the COE by 12%. Remember that the net electric power is held constant; therefore, a more efficient power unit is smaller and suffers an economy of scale penalty. That is, the cost per $kW_t$ is only the same for plants of equal thermal power. The minima of the dashed curves is not strongly affected by changes in $\eta_c$.

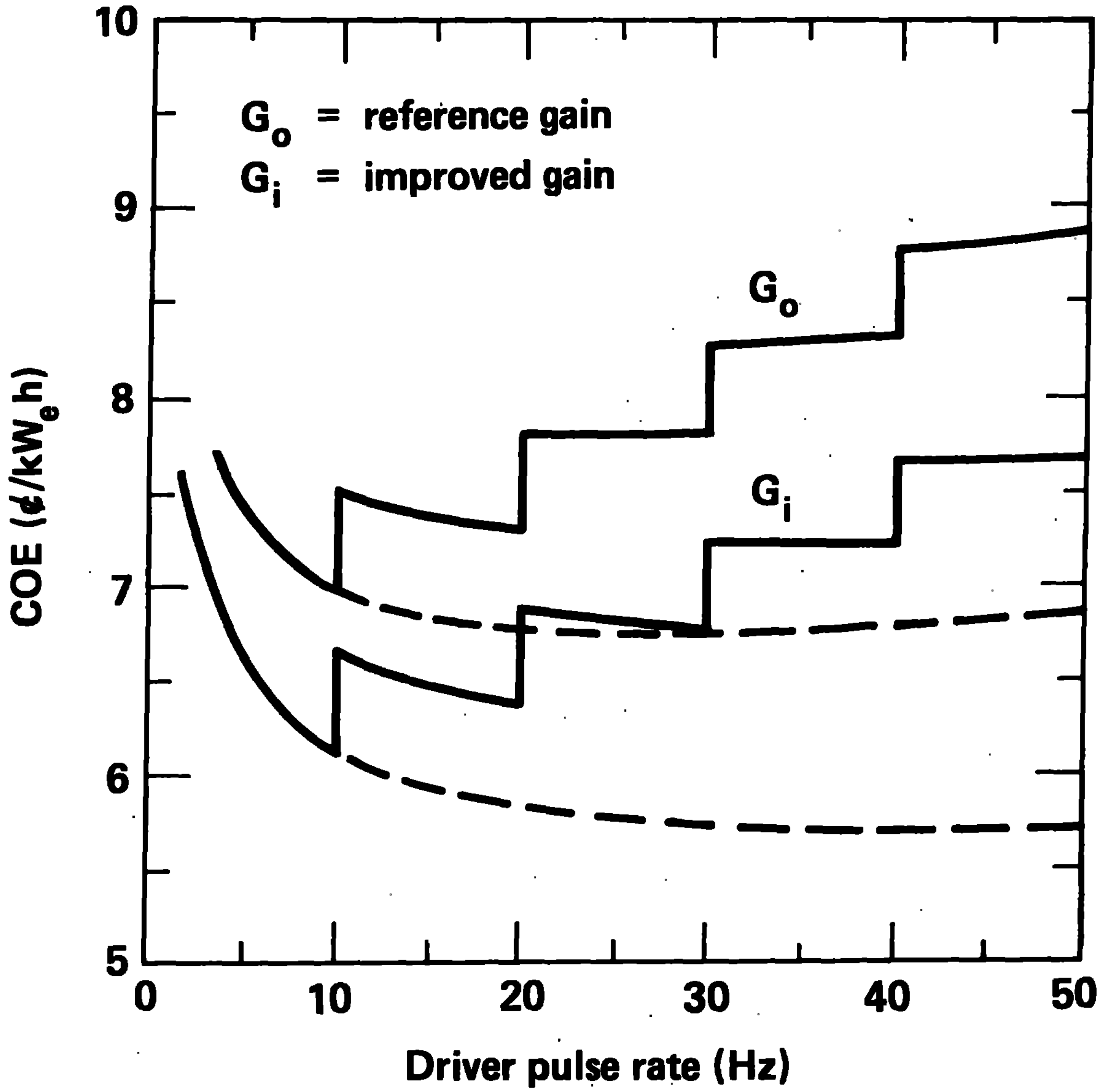


Fig. /. Improved target performance leads to a lower COE.

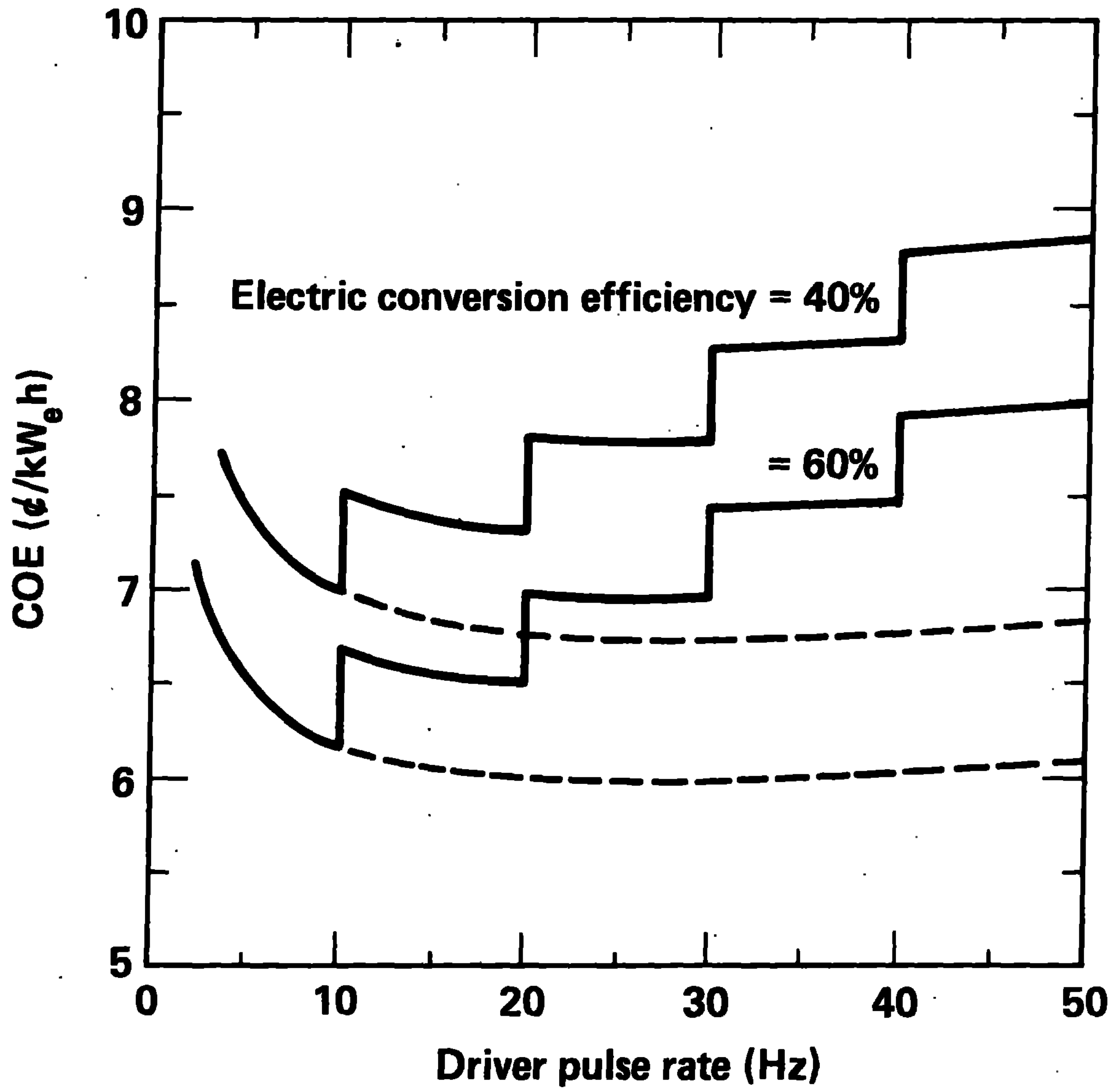


Fig. 8. Increasing the electric conversion efficiency reduces the COE.

Plant Power as a Parameter

As noted previously, there are two ways to consider net plant power as a variable. The value of $N_u$ can be set equal to one (i.e., one power unit per plant) and we can allow the size of the power unit to grow (maintaining the possibility of having multiple chambers). On the other hand, we can keep the power per unit constant and change $N_u$ (place more than one power unit in a plant). First, we consider a single unit plant.

Figure 9 shows the COE for net power outputs of 0.5, 1.0 and 2.0 $GW_e$. The COE from the 0.5-$GW_e$ plant is 66% greater than the base case at 10 Hz (11.6 vs 7.0¢/$kW_e$h). The 2.0-$GW_e$ plant produces electricity at 4.3¢/$KW_e$h, or at 39% less cost than the base case. It is clearly advantageous, in terms of the COE, to use the driver to produce as much power as possible. Other considerations, such as following the utility's load growth and minimizing the total capital investment, may favor the smaller net powers.

The advantage of using a single driver and target factory to operate more than one power unit is shown in Fig. 10. The three curves from top to bottom represent 1-, 2-, and 4-unit plants, respectively. The net power from the plants is $N_u$ $GW_e$; that is, each unit produces 1 $GW_e$. Note that the initial jump in the COE is at $N_u \omega_{cm}$. For example, with $\omega_{cm}$ = 10 Hz and $N_u$ = 2, the driver pulse rate can be increased to 20 Hz before more chambers are required.

At a driver pulse rate of 20 Hz, the two-unit power plant produces electricity at 4.8¢/$kW_e$h, or 32% less cost than the single-unit plant. The four-unit plant reduces the COE to 3.6¢/$kW_e$h, or 49% less cost than the single-unit plant. The total capital investment, however, increases as the

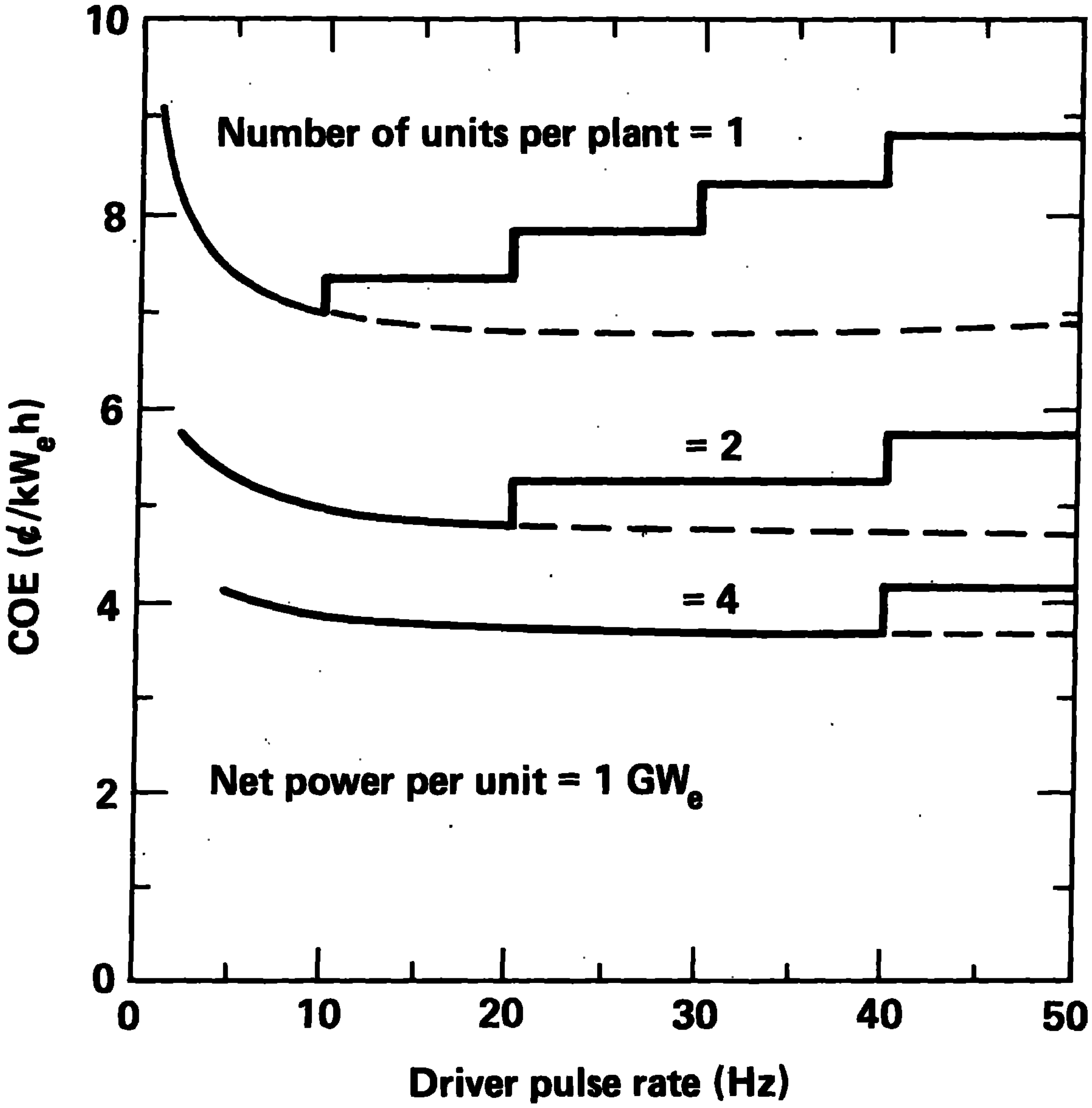


Fig. 9. Using a single driver to operate more than one full-size power unit reduces the COE significantly.

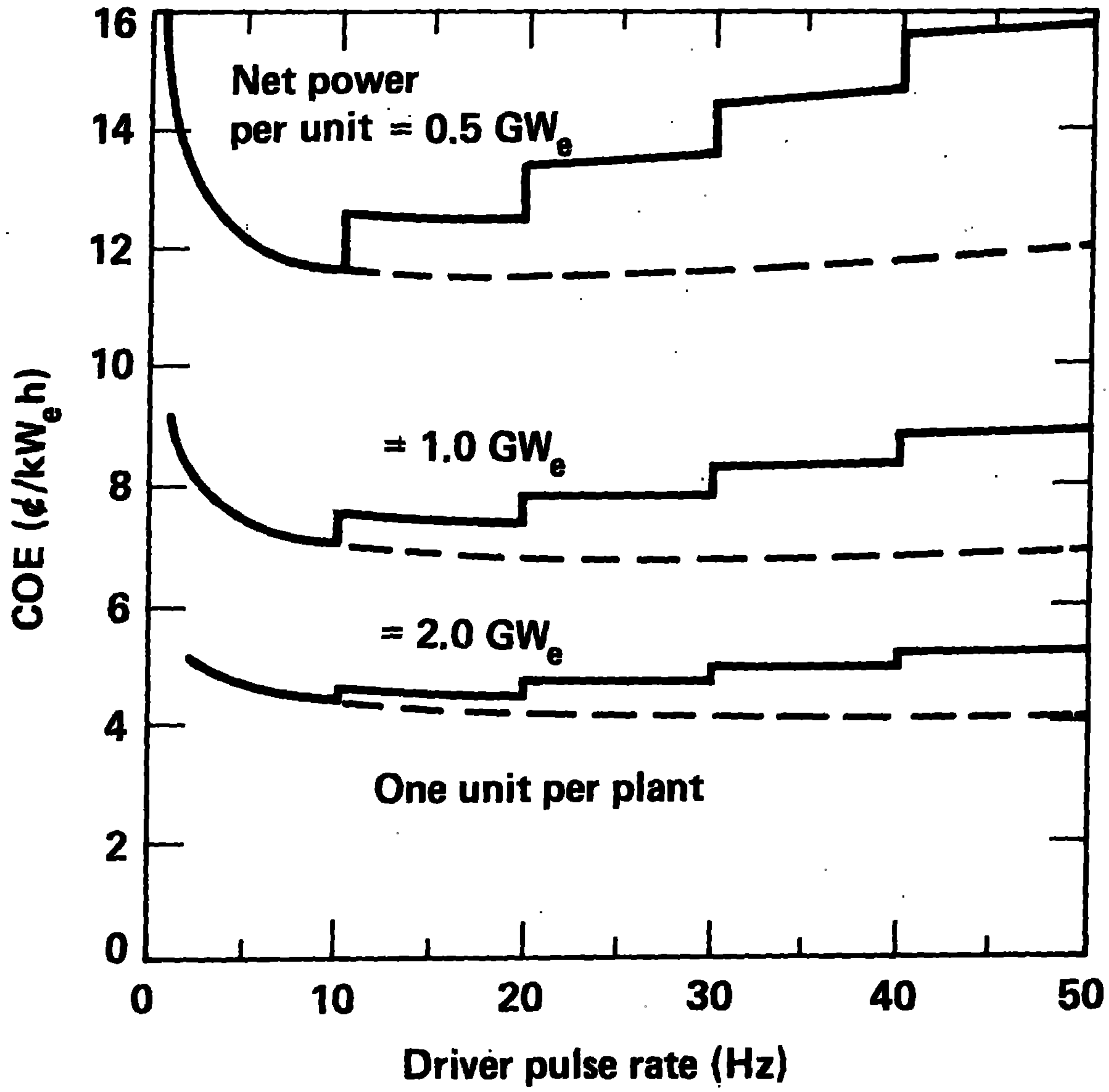


Fig. 10. The COE decreases as the plant's net power increases.

number of units is increased. Total capital costs for the 1-, 2- and 4- unit plants are $3.4, $4.7, and $7.1 billion, respectively.

We found that as the number of power units increases, the COE becomes less sensitive to the driver pulse rate. The four-unit plant could operate at a driver pulse rate of 12 Hz and still be within 5% of its minimum COE. The required chamber pulse rate in this case is only 3 Hz.

Figure 11 shows the COE as a function of the total net power for plants made up of different size units: 0.5, 1.0, 1.5 and 2.0 $GW_e$ net. The COE from a 1.0-$GW_e$ power plant consisting of two 0.5-$GW_e$ units and a single driver is 7.7¢/$KW_e$h. This is 10% higher than the COE from a single-unit power plant generating 1 $GW_e$. This higher COE is the result of the economies of scale in the power unit cost and the additional cost of beam-transport lines for the two-unit plant.

If the cost-scaling relationships [Eqs. (4) and (5)] holds as we scale up to a 2-$GW_e$ power unit, the COE for a power plant with a single 2-$GW_e$ unit is 4.3¢/$KW_e$h compared to 4.8¢/$KW_e$h for a two-unit 2-$GW_e$ plant. At 5.8¢/$kW_e$h, the four-unit, 2-$GW_e$ plant is significantly more expensive. We see that at a fixed net power, the COE is lower for a single-unit plant than for a multi-unit plant. The multi-unit plant does, however, achieve most of the economy of scale benefits of a single large unit. For example, going from 0.5 to 2 $GW_e$ in single-unit plant reduces the COE by 63%, compared to the 50% reduction achieved by a four-unit plant. An advantage of the multi-unit plant is its operational flexibility. The plant can begin to operate and produce revenues from one unit while decisions are pending on the need for additional units. Capital costs for the future units are, of course, also deferred.

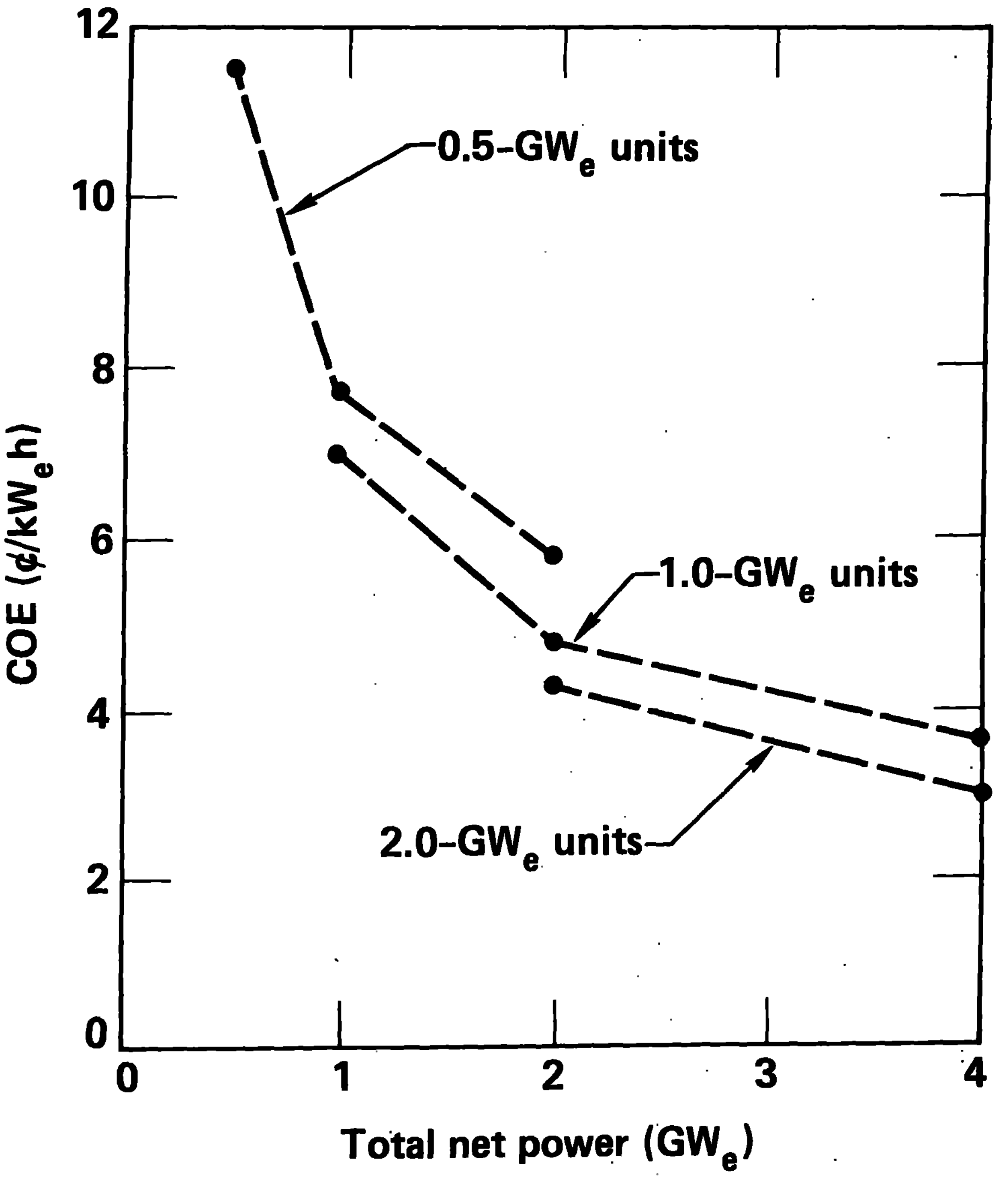


Fig. 11. For the same net power, plants with fewer, larger power units have lower COEs.

Several Parameters Simultaneously

Most of the parameters considered have a modest impact on the COE. No single improvement considered is able to reduce the COE to the point where it would be competitive with coal (4.6¢/$KW_e$h) or nuclear (3.6¢/$KW_e$h) power.[2] Hence it is important to make advances in as many areas as possible. In Fig. 12 several improvements are considered simultaneously for the three different net power outputs. These curves are based on a maximum chamber pulse rate of 10 Hz, a driver cost reduction of 25%, the improved target gain, an electric conversion efficiency of 50%, and two-unit power plants. The plant net powers are 1, 2 and 3 $GW_e$. While the 1-$GW_e$ plant is still not economically competitive with coal and nuclear power, the 2- and 3-$GW_e$ plants are quite competitive.

## CONCLUSIONS

We have examined the COE of HIB fusion power plants in order to determine the economic impact of various design and system improvements. Our conclusions fall into four major areas: (1) optimum pulse rate, (2) multiple reaction chambers, (3) economy of scale, and (4) various design improvements.

Optimum Pulse Rate

For the single-unit, 1-$GW_e$ power plant, the optimum pulse rate (for both driver and chamber) is 25 to 30 Hz, resulting in a COE of 6.75¢/$kW_e$h. However, the COE is not very sensitive to pulse rate. For example, if the chamber pulse rate is limited to 5 Hz, the COE increases by less than 10%.

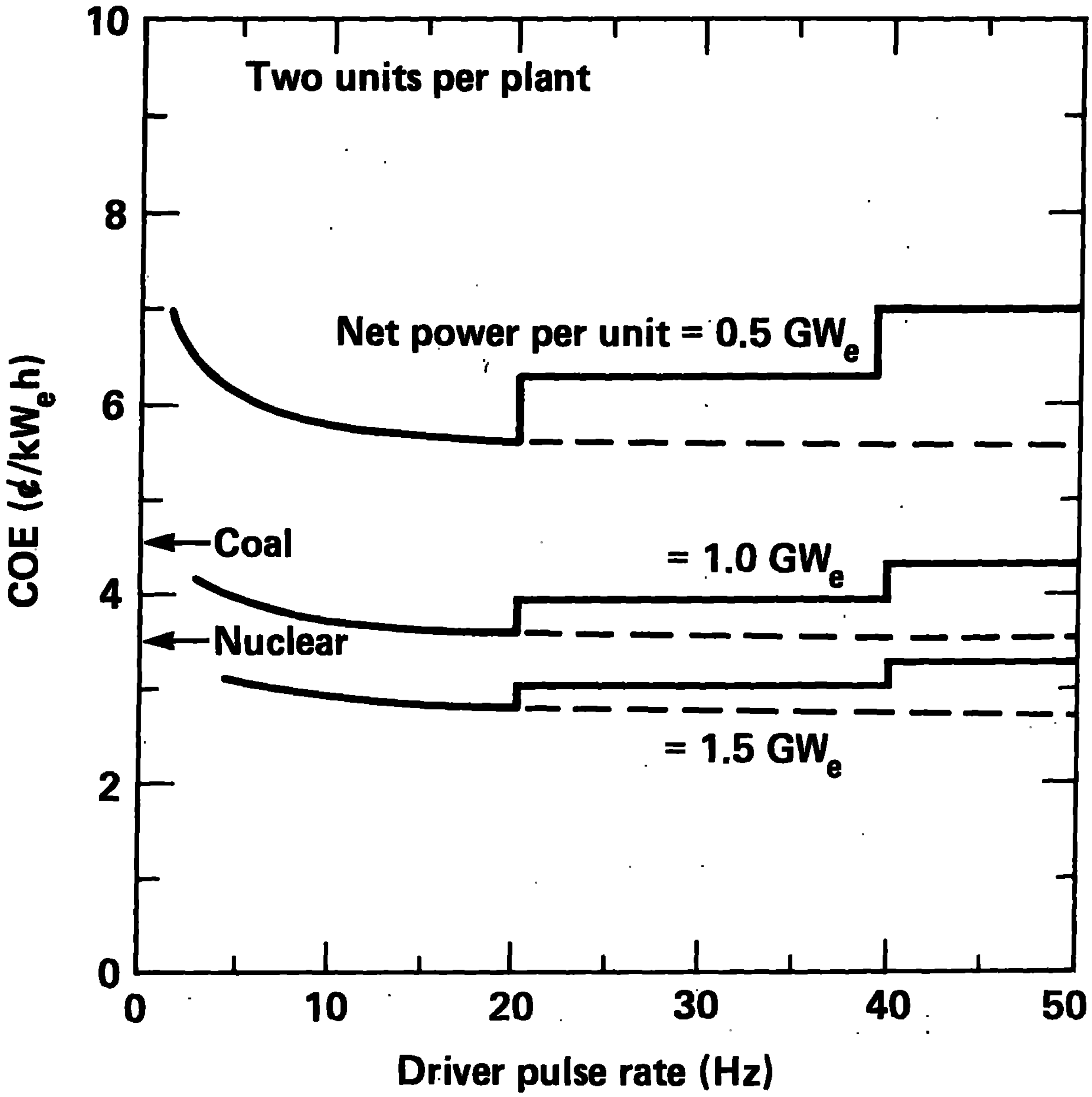


Fig. 12. With several simultaneous improvements, the COE from HIB fusion electric power plants will be competitive with nuclear and coal power plants.

This weak dependence of COE on pulse rate is important because major technological uncertainties are associated with predicting the maximum achievable chamber pulse rate. Decreasing the driver cost or increasing the plant size results in a lower optimum pulse rate, and the COE becomes even less sensitive to pulse rate. Improving the target gain (which corresponds to reducing the required driver energy for a given gain) results in a higher optimum pulse rate. Increasing the electric conversion efficiency has little effect on the location of the optimum pulse rate.

## Multiple Reaction Chambers

For the conditions examined here, using multiple reaction chambers at constant net power never improved the COE. The optimum driver pulse rate in every case was at the maximum achievable pulse rate of a single reaction chamber. This was due to the large cost ($100 million direct) of adding beam-transport lines for each new chamber and to the insensitivity of the COE to pulse rate.

## Economy of Scale

As expected, the COE decreases with increasing net electric power. The reduction is significant, whether the power is increased by increasing the power of a single unit, or by using a single driver to operate several power units. These savings result from the driver being such a large fraction of the plant cost. Only if the cost of the driver is significantly reduced will the penalty for small power units be significantly affected.

For a given net power, a multi-unit plant achieves most of the economy-of-scale advantage of a single large plant. Because the advantage difference between the multi-unit and single-unit plant is so small, starting with a small unit (0.5 $GW_e$ or less) and adding power units might be particularly attractive. In this way, revenues can be collected from the first units, and the later units can be constructed as needed. Other advantages of smaller units, such as reduced on-site construction costs due to increased factory fabrication and shortened construction periods, have not yet been considered in our studies. These will tend to reduce the COE penalty of plants comprised of several smaller power units.

Various Design Improvements

Reducing the HIB driver cost is important: a 25% reduction in the driver cost leads to a 13% reduction in the COE. Improving target performance is also important. If the same target gain can be achieved with a factor of 3 less driver energy, the COE can be reduced by 12%. Improving the electric conversion efficiency is not as advantageous as might be expected. Increasing the conversion efficiency from 40 to 60% reduces the COE by 12%, assuming the power unit cost per $kW_t$ does not increase with increasing efficiency. If it does increase, the savings will be even less.

Only a combination of improvements reduces the COE to values in the range of those forecast for future coal and fission plants. Such a combination of improvements is not unreasonable, however. If the driver cost is reduced 25%, the target gain improved at low $E_d$, the electric conversion efficiency increased to 50%, and a two-unit plant is built (2 $GW_e$ total), then the COE is competitive.

## APPENDIX A. CALCULATION OF THE FIXED CHARGE RATE

The fixed charge rate can be calculated from the following expression,[2,11]

$$R = \frac{C}{(1 - t)} - \frac{td}{(1 - t)} + t_p + r \qquad \text{(A.1)}$$

where

$C$ = $C(x,n)$ = capital recovery factor,

$x$ = effective after-tax annual cost of money,

$n$ = plant life in years,

$t$ = income tax rate,

$d$ = levelized tax depreciation,

$t_p$ = property tax rate, and

$r$ = levelized interim replacement cost.

The effective after-tax cost of money (x) accounts for the fact that investment capital is raised from a variety of sources, and the interest paid on debt financing is tax deductible. It is calculated from[2,11]

$$x = i_c f_c + i_p f_p + (1 - t) i_d f_d \quad , \qquad \text{(A.2)}$$

where

$i_c$ = rate of return on common stock,

$f_c$ = fraction of capital from common stock,

$i_p$ = rate of return on preferred stock,

$f_p$ = fraction of capital from preferred stock,

$i_d$ = interest rate on debt, and

$f_d$ = fraction of capital from debt.

For this study, we used $i_c = 14\%$, $f_c = 40\%$; $i_p = 11\%$, $f_p = 10\%$; and $i_d = 10\%$, $f_d = 50\%$. According to other studies,[2,12] these are typical of electric utilities. With a typical combined state and federal tax rate, t, of 50%, x is found to be 9.2%.

The capital recovery factor is calculated from

$$C = \frac{x(1 + x)^n}{(1 + x)^n - 1} \quad . \tag{A.3}$$

With n = 30 years and x = 9.2%, we get C = 0.099.

We assume straight-line depreciation. Therefore, d is given by

$$d = f/30 \quad , \tag{A.4}$$

where f is the fraction of the initial investment that is depreciable for tax purposes. This "f" factor is calculated from

$$f = (1 + x)^{-0.4\tau} \quad , \tag{A.5}$$

where $\tau$ = construction period in years. With $\tau$ = 8 years and x = 9.2%, we get f = 0.75 and d = 0.025.

Using the above results along with a property tax rate ($t_p$) of 2%, and an interim replacement cost (r) of 1% per year results in a fixed-charge rate of 20.3%.

For a constant dollar analysis, in which the purchasing power of the dollar does not change with time, the fixed charge rate must be adjusted to reflect the real cost of money; i.e., the inflation-free cost of money. The constant dollar fixed charge rate is given by[2]

$$R_C = RC(x_r,n)/C(x,n) \quad , \tag{A.6}$$

where

$R$ = current dollar fixed charge rate from Eq. A.1, and

$x_r$ = real cost of money.

The real cost of money is given by

$$x_r = (1 + x)/(1 + i) - 1 \tag{A.7}$$

where i is the annual inflation rate. For our study, i = 6.0%. Hence, $x_r$ = 3.0%, and $R_C$ is found to be 10.5%. Note that this adjustment also accounts for the fact that payments that do not change with time, such as the annual property tax, are decreasing in reference year dollars.

## APPENDIX B. CALCULATIONS OF TIME-RELATED COSTS

The effects of escalation and interest during construction can be accounted for by multiplying the direct plus indirect construction costs by a factor $f_{TC}$. This time-related cost factor can be calculated from

$$f_{TC} = (1 + e)^{0.6\tau}(1 + x)^{0.4\tau} \quad , \tag{B.1}$$

where e is the annual escalation rate, x is the after-tax cost of money, and $\tau$ is the construction period. We assume that the reference year corresponds to the start of construction. This simple formula gives results which agree closely with the results published by Phung[13] and used in Ref. 8. In our study, with $e = 6.0\%$, $x = 9.2\%$ and $\tau = 8$ years, we get $f_{TC} = 1.75$. Hence, the total expenditure over the 8-year construction period is 75% greater than the "overnight" construction cost estimated at the start of construction. For a constant dollar analysis, the capital cost must be expressed in reference-year dollars. Therefore, the time-related cost factor for a constant dollar approach is

$$f_{TC} = (1 + e)^{0.6\tau} (1 + x)^{0.4\tau} / (1 + i)^{\tau} \quad , \tag{B.2}$$

where i is the inflation rate. If the escalation rate and the inflation rate are equal,

$$f_{TC} = (1 + x)^{0.4\tau}/(1 + i)^{0.4\tau} = (1 + x_r)^{0.4\tau} \quad , \tag{B.3}$$

where $x_r$ is the real cost of money (see App. A). With $x_r = 3.0\%$, we get $f_{TC} = 1.099$.

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